ATTACHMENT B

A Guide for Establishing GPS-Derived Orthometric Heights (Standards: 2 cm and 5 cm)

Version 1.3

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A GUIDE FOR ESTABLISHING GPS-DERIVED ORTHOMETRIC HEIGHTS
[Standards: 2 cm and 5 cm]
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Preface:

In November 1997, guidelines were developed by the National Geodetic Survey (NGS) for performing Global Positioning System (GPS) surveys that are intended to achieve **ellipsoid height *network* accuracies** of 5 cm at the 95 percent confidence level, as well as **ellipsoid height *local* accuracies** of 2 cm and 5 cm, also at the 95 percent confidence level (Zilkoski et al. 1997). See Appendix A for information about local and relative ellipsoid height accuracies and Appendix B for information on the basic requirements for 2-cm ellipsoid height standards.

The following guidelines were developed by NGS for performing GPS surveys that are intended to achieve **orthometric height *network* accuracies** of 5 cm at the 95 percent confidence level, as well as **orthometric height *local* accuracies** of 2 cm and 5 cm, also at the 95 percent confidence level. These guidelines were developed in partnership with Federal, state, and local government agencies, academia, and private surveyors.

We are confident that these guidelines, if followed, will result in achieving the intended accuracy. Additional analysis may show that some of these guidelines can be relaxed in the future. These guidelines are intended for establishing vertical control networks.

Note: these guidelines assume that for the survey project area in question, NGS has completed the establishment of a high accuracy reference network at 100-kilometer spacing or that a state-wide High Accuracy Reference Network (HARN) has been established, i.e., there are A- or B-order stations distributed throughout the state at an approximate spacing of 50 km or else there are Federal HARN stations or GPS Continuously Operating Reference Station (CORS) sites located within 75 km of the project area.

An effort should be made to connect to stations which were previously determined using these guidelines (or equivalent).

Introduction:

Since early 1983, NGS has performed control survey projects in the United States using GPS satellites. Analysis of GPS survey data has shown that GPS can be used to establish precise relative positions in a three-dimensional Earth-centered coordinate system. GPS carrier phase measurements are used to determine vector base lines in space, where the components of the base line are expressed in terms of Cartesian coordinate differences (Remondi 1984). These vector base lines can be converted to distance, azimuth, and ellipsoidal height differences (dh) relative to a defined reference ellipsoid.

During the past decade, results from projects have clearly shown that GPS survey methods can replace classical horizontal control terrestrial survey methods. However, until recently, there was a problem in obtaining sufficiently accurate geoid height differences to convert GPS-derived ellipsoid height differences to accurate GPS-derived orthometric height differences (Zilkoski and Hothem 1989, Hajela 1990, Milbert 1991). The interest in obtaining accurate GPS-derived orthometric heights has increased during the last several years (Parks and Milbert 1995, Kuang et al. 1996, Satalich 1996, Zilkoski and D'Onofrio 1996, Henning et al. 1998, Martin 1998). Can the accuracies achieved for these orthometric height differences now provide a viable alternative to classical geodetic leveling techniques? With the completion of the general adjustment of the North American Vertical Datum of 1988 (NAVD 88) (Zilkoski et al. 1992), computation of an accurate National high-resolution geoid model, GEOID99 (*Smith and Roman 2000*), and development of NGS' Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm) (Zilkoski et al. 1997), the answer is yes -- GPS-derived orthometric heights can now provide a viable alternative to classical geodetic leveling techniques for many applications.

Orthometric heights (H) are referenced to an equipotential reference surface, e.g., the geoid. The orthometric height of a point on the Earth's surface is the distance from the geoidal reference surface to the point, measured along the plumb line normal to the geoid. Ellipsoid heights (h) are referenced to a reference ellipsoid. The ellipsoid height of a point is the distance from the reference ellipsoid to the point, measured along the line which is normal to the ellipsoid. At the same point on the surface of the earth, the difference between an ellipsoid height and an orthometric height is defined as the geoid height (N).

Several error sources that affect the accuracy of orthometric, ellipsoid, and geoid height values are generally common to nearby points. Because these error sources are in common, the uncertainty of height differences between nearby points is significantly smaller than the uncertainty of the absolute heights of each point.

Orthometric height differences (dH) can then be obtained from ellipsoid height differences by subtracting the geoid height differences(dN):

$$dH \approx dh - dN.$$

Adhering to NGS' guidelines, ellipsoid height differences (dh) over **short base lines**, i.e., less than 10 km, can now be determined from GPS phase measurements with 2-sigma uncertainties that are **typically better than +/- 2 cm.** This is now possible because of the availability of a greater number of satellites, more accurate satellite orbits, full-wavelength dual-frequency carrier phase data, improved antenna designs, and improved data processing techniques. It should also be noted that the GPS-derived ellipsoid height guidelines documented by Zilkoski et al.(1997)were intentionally designed to produce ellipsoid heights slightly better than 2 cm, i.e., about 1.4 cm, so that they could also be used when generating 2-cm GPS-derived orthometric heights. The requirement that each base line must be repeated and agree to within 2 cm of each other, and because they must be obtained on two separate days during different times of the day provide a final GPS-derived ellipsoid height better than 2 cm at the 2-sigma level. The requirement that spacing between local network station cannot exceed 10 km helps to keep the relative error in geoid height small, i.e., typically less than 0.5 cm. Adding in the small error for the uncertainty of the geoid height difference and controlling the remaining systematic differences between the three height systems will produce a GPS-derived orthometric height with 2-sigma uncertainties that are typically +/- 2 cm.

In many areas of the United States, geoid height differences can be determined with uncertainties that are typically better than 1 cm for distances of as much as 20 km and less than 2-3 cm for distances from 20 to 50 km (Zilkoski and D'Onofrio 1996, and Henning et al. 1999). The small values for the differential geoid height uncertainties have been demonstrated in tests in several regions of the United States. Larger uncertainties can be expected in other areas, depending on the density of the observed gravity network and uncertainties in the determination of observed and interpolated gravity anomalies.

When high-accuracy field procedures are used, orthometric height differences can be computed from measurements of precise geodetic leveling with an uncertainty of less than 1 cm over a 50-kilometer distance. Less accurate results are achieved when third-order leveling methods are employed. Depending on the accuracy requirements, GPS surveys and present high-resolution geoid models can be employed as an alternative to classical leveling methods. In the past, the primary limiting factor was the accuracy of estimating geoid height differences. With the computation of the latest National high-resolution geoid model, GEOID99, and the development of the 2- and 5-cm guidelines for estimating GPS-derived ellipsoid heights (Zilkoski et al. 1997), the limiting factor is ensuring that the NAVD 88 orthometric height values used to control the project are valid. Strategically occupying bench marks with GPS that have valid NAVD 88 height values is critical to detecting, reducing, and/or eliminating blunders and systematic errors between the three height systems.

The 3-4-5 System:

There are three basic rules, four control requirements, and five procedures which need to be adhered to for estimating GPS-derived orthometric heights. This document describes these rules, control requirements, and procedures required for estimating GPS-derived orthometric height to meet 2- and 5-cm standards. It is the intent of this document to keep the explanation of rules, requirements, and procedures to a minimum. Detailed explanations can be found in the referenced reports.

Basic **Rules** for Estimating GPS-Derived Orthometric Heights:

There are three basic rules that a user must follow when estimating accurate GPS-derived orthometric heights:

Rule 1: Follow NGS' guidelines for establishing GPS-derived ellipsoid heights when performing GPS survey (Zilkoski et al. 1997),

Rule 2: Use NGS' latest National Geoid Model, i.e., GEOID99, when computing GPS-derived orthometric heights (Smith and Roman 2000), and

Rule 3: Use the latest National Vertical Datum, i.e., NAVD 88, height values to control the project's adjusted heights (Zilkoski et al. 1992).

Basic **Control Requirements** for Estimating GPS-Derived Orthometric Heights:

When the user follows the three basic rules above, there are only four basic control requirements for estimating GPS-derived orthometric heights:

Requirement 1: GPS-occupy stations with ***valid*** NAVD 88 orthometric heights, stations should be evenly distributed throughout project.

Requirement 2: For project areas less than 20 km on a side, surround project with ***valid*** NAVD 88 bench marks, i.e., minimum number of stations is four; one in each corner of project. *[NOTE: The user may have to enlarge the project area to occupy enough bench marks even if the project area extends beyond the original area of interest.]*

Requirement 3: For project areas greater than 20 km on a side, keep distances between ***valid*** GPS-occupied NAVD 88 bench marks to less than 20 km.

Requirement 4: For projects located in mountainous regions, occupy ***valid*** bench marks at base and summit of mountains, even if distance is less than 20 km.

[NOTE: Valid NAVD 88 height values include, but are not limited to, the following: bench marks which have not moved since their heights were last determined, were not misidentified, and are consistent with NAVD 88.]

Basic **Procedures** for Estimating GPS-Derived Orthometric Heights:

When the user follows the three basic rules and four control requirements stated above, there are only five basic procedures that need to be followed for computing accurate GPS-derived orthometric heights.

Procedure 1: Perform a 3-D minimum-constraint least squares adjustment of the GPS survey project, i.e., constrain one latitude, one longitude, and one orthometric height value.

Procedure 2: Using the results from the adjustment in procedure 1 above, detect and remove all data outliers. *[NOTE: If the user follows NGS' guidelines for establishing GPS-derived ellipsoid heights, then the user will already know which vectors may need to be rejected and following the GPS-derived ellipsoid height guidelines should have already reobserved those base lines.]*

The user should repeat procedures 1 and 2 until all data outliers are removed.

Procedure 3: Compute differences between the set of GPS-derived orthometric heights from the minimum constraint adjustment (using the latest National geoid model, i.e., GEOID99) from procedure 2 above and published NAVD 88 bench marks.

Procedure 4: Using the results from procedure 3 above, determine which bench marks have ***valid*** NAVD 88 height values. This is the most important step of the process. Determining which bench marks have valid heights is critical to computing accurate GPS-derived orthometric heights. *[NOTE: The user should include a few extra NAVD 88 bench marks in case some are inconsistent.]*

All differences between valid bench marks need to agree within 2 cm for 2-cm surveys and 5 cm for 5-cm surveys. *[NOTE: For most small areal extent, e.g., 20 km by 20 km, in the conterminous United States, using NGS' latest National Geoid Model should produce satisfactory results (see Hennings et. al, 1998). There may, however, appear to be a systematic tilt over large areas, i.e., 50 km by 50 km, but with NAVD 88 vertical control occupied with GPS every 20 km, this tilt should be accounted for in the final constrained adjustment. The user should estimate local systematic differences between GPS-derived heights and leveling-derived heights by solving for the geoidal slope and scale. [See Vincenty (1987)and Zilkoski 1993].*

Procedure 5: Using the results from procedure 4 above, perform a constrained adjustment fixing one latitude and one longitude value and all ***valid*** NAVD 88 height values.

The user should always ensure that the final set of heights weren't distorted by the adjustment process. If the user followed the procedures outlined above, then this should not occur, but there is a fairly simple way of checking for blunders.

The user should compute the differences between the final set of GPS-derived orthometric heights from procedure 5 and the minimum constrained set of heights from procedure 2. The differences <u>between neighboring stations</u> should be small, i.e., 1 cm (see Henning et al., 1998). If these differences exceed 2 cm, it is possible that an incorrect or invalid station value was held fixed.

During the last decade, several NGS reports have been prepared that describe these procedures in more detail (Zilkoski and Hothem, 1989; Zilkoski, 1990a; Zilkoski, 1990b; Zilkoski, 1993;and Henning, et. al, 1998). These reports are available from NGS' web site at http://www.ngs.noaa.gov. Although, it should be mentioned that because of improvements in high resolution geoid models, the implementation of the full constellation of GPS, the completion of the NAVD 88 project, improvements in GPS equipment and processing software, and the development of guidelines for estimating GPS-derived ellipsoid heights, the minimum steps outlined in the above reports only need to be considered when a problem is detected when performing the five procedures. However, the reports, even thought they are slightly out of date because of improvements in geoid models and technology, should provide the necessary information for the user to understand how to perform the five procedures stated in these guidelines. In particular, the report titled “NGS/Caltrans San Diego GPS-Derived Orthometric Height Cooperative Project” demonstrates the minimum steps required to estimate and evaluate a GPS-derived orthometric height project. Today, the 10 steps are simplified into five procedures, but they may still need to be considered when doing some projects. Appendix C contains a list of the 10 steps outlined in the San Diego GPS Project report and appendix D contains a brief description of the five procedures using a sample project.

<u>Submission of Data to the National Geodetic Survey:</u>

"Input Formats and Specifications of the National Geodetic Survey (NGS) Data Base," commonly called the "Blue Book," is a user's guide for preparing and submitting geodetic data for incorporation into NGS' data base. Survey data that are entered into NGS' data base become part of the National Spatial Reference System (NSRS), formerly the National Geodetic Reference System. The guide comprises three volumes. Volume I covers classical horizontal geodetic and Global Positioning System (GPS) data, volume II covers vertical geodetic data, and volume III covers gravity data. Beginning with this edition, the three formerly separate volumes are distributed as a set, since a great deal of information is common to each volume. Because some of the chapters and annexes are identical in all three volumes, the original numbering design has been retained.

The formats and specifications are consistent with the aims of the Executive Office of the President, Office of Management and Budget's (OMB) Circular A-16, as revised in 1990. A major goal of the circular, which is titled "Coordination of Surveying, Mapping, and Related Spatial Data Activities," is to develop a national spatial data infrastructure with the involvement of Federal, state, and local governments, and the private sector. This multilevel national information resource, united by standards and criteria established by the Federal Geodetic Control Subcommittee (FGCS) of the Federal Geographic Data Committee (FGDC), will enable the sharing and efficient transfer of geospatial data between producers and users.

Survey data that are submitted to NGS for incorporation into NSRS should be properly formatted and follow the guidelines outlined in this report.

The “Blue Book” and most of the documents referenced herein may be obtained from NGS web site at http://www.ngs.noaa.gov/FGCS/BlueBook/ or

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Monday through Friday, 7:00 a.m. - 4:30 p.m. Eastern Time.

Data Submission to NGS:

1. The project accession number is of the form GPS-xxx. (The project accession number <u>**will be *assigned by NGS when draft project plans are submitted to NGS for evaluation prior to the start of the project***</u>.)

2. A project report and the data elements listed in Appendix L of "Input Formats and Specifications of the NGS Data Base" must be transmitted to NGS. Quality checks for conformance to NGS format standards shall be performed using software programs COMPGB and OBSDES.

3. Latitude, longitude, and ellipsoid heights, as well as X, Y, and Z coordinates shall be provided in both NAD 83 and ITRF coordinate systems. GPS-derived orthometric heights shall be provided in NAVD 88.

Guideline Updates:

These Guidelines will be updated as the results of future projects and other procedures are reviewed. There may be other procedures that will also achieve the standards. The user should note which procedures in this document were not followed and note how errors and systematic biases were detected, reduced, or eliminated by the new procedure. NGS welcomes the opportunity to examine alternate procedures and supporting data that demonstrate the ability to achieve the accuracy standards stated in this document. If you have such data or would like to comment, please contact Dave Zilkoski or Edward Carlson, telephone 301-713-3196, or write:

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Appendix A. -- Definitions

Accuracy

Local Accuracy - The local accuracy of a control point is a value expressed in cm that represents the uncertainty in the coordinates of the control point relative to the coordinates of the other directly connected, adjacent control points at the 95 percent confidence level. The reported local accuracy is an approximate average of the individual local accuracy values between this control point and other observed control points used to establish the coordinates of the control point.

Network Accuracy - The network accuracy of a control point is a value expressed in cm that represents the uncertainty in the coordinates of the control point with respect to the geodetic datum at the 95 percent confidence level. For National Spatial Reference System (NSRS) network accuracy classification, the datum is considered to be best supported by NGS. By this definition, the local and network accuracy values at CORS sites are considered to be infinitesimal, i.e., to approach zero.

Stations

Base Stations

Primary - Stations evenly distributed that surround the local network. These stations relate the local network to NSRS to the 5-cm, or better, standard through simultaneous observations with control stations. They can be newly established stations and be part of the local network.

Secondary - Stations evenly distributed throughout the local network that ensure that the local network does not contain a significant medium wavelength (20-30 km) ellipsoid height error through simultaneous observations with primary base stations. These stations may be newly established stations and are part of the local network. They are located between Primary Base Stations.

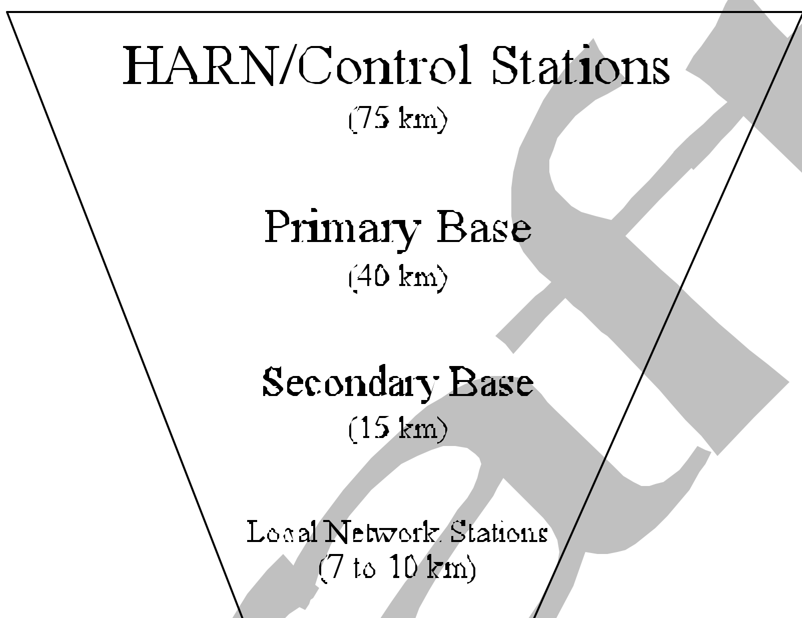
Control Stations

A- or B-order three-dimensional stations that surround the project area in at least three different quadrants. These stations relate the local network to the National Spatial Reference System through simultaneous observations with primary base stations. They must be referenced to NSRS and they provide the network accuracy. They may be newly established stations in the survey project if A- or B-order specifications and procedures are used to establish them. These procedures are not covered in this document, please contact NGS for additional information.

Local Network Stations

These stations include all other stations that are not base (primary or secondary) or control stations. They are part of the local network. They provide the local accuracy standard through simultaneous observations between adjacent stations.

Appendix B. -- GPS Ellipsoid Height Hierarchy and Basic Requirements for 2-cm standard



HARN/Control Stations

O CS1

O CS2 **<-------------------- 75 km ------------------->** O CS3

Primary Base Stations

O CS1

PB1

PB2 <---------------------- 40 km ---------------------> PB3

O CS2 CS3 O

Basic Requirements

o 5 Hour Sessions / 3 Days

o Spacing between primary base stations cannot exceed 40 km.

o Each primary base station must be connected to at least its nearest primary base station neighbor and nearest control station.

o Primary base stations must be traceable back to 2 control stations along independent paths; i.e, base lines PB1 - CS1 and PB1 - PB2 plus PB2 -CS2, or PB1 - CS1 and PB1 - PB3 plus PB3 - CS3.

Secondary Base Stations

O

PB1

SB1 ***SB2***

SB3 <---------- 15 km ----------> SB4

PB2 PB3

O O

Basic Requirements

o 30 Minute Sessions / 2 Days / Different Times of the Day

o Spacing between secondary base stations (or between primary and secondary base stations) cannot exceed 15 km.

o All base stations (primary and secondary) must be connected to at least its two nearest primary or secondary base station neighbors.

o Secondary base stations must be traceable back to 2 primary base stations along independent paths; i.e., SB1- PB1 and SB1- SB3 plus SB3 - PB2,
or SB1 - PB1 and SB1 - SB4 plus SB4 - PB3.

o Secondary base stations need not be established in surveys of small areal extent.

Local Network Stations

O

PB1

LN1

SB1 ***LN2*** ***LN3*** SB2

LN4 **LN5**

LN6<--7 km -> LN7

SB3 SB4

PB2 PB3

O O

Basic Requirements

o 30 Minute Sessions / 2 Days / Different Times of the Day

o Spacing between local network stations stations (or between base stations and local network stations) cannot exceed 10 km.

o All local network stations must be connected to at least its two nearest neighbors.

o Local network stations must be traceable back to 2 primary base stations along independent paths; i.e., LN1 - PB1 and LN1 - LN2, plus LN2 - SB1, plus SB1 - SB3 plus SB3 - PB2, or LN1 - PB1 and LN1 -LN3, plus LN3 - SB2 plus SB2 - SB4 plus SB4 - PB3.

APPENDIX C. – 10 Minimum Steps Required to Estimate and Evaluate a GPS-Derived Orthometric Height Project.

These steps are documented in the report titled “Minimum Steps Required When Estimating GPS-Derived Orthometric Heights,” Proceedings of the GIS/LIS ‘90 Fall Convention, Anaheim, California, November 7-10.

The minimum steps required when analyzing GPS-derived orthometric heights are listed below.

1. During the project’s planning stage, perform a detailed analysis of the geoid in the area of the survey in order to determine if additional gravity and/or leveling data are required to adequately estimate the slope of the geoid and changes in slope.

2. During the project’s planning stage, perform a detailed study of the leveling network in the area, i.e., plot all leveling lines, note the age of leveling, determine if bench marks can be occupied by GPS receivers, etc.

3. Perform a 3-D minimum constraint least squares adjustment of the GPS data and compare GPS-derived coordinates with results of higher-order surveys.

4. Using the best available geoid heights, compare adjusted GPS-derived orthometric height differences obtained from step 3 with leveling-derived orthometric height differences.

5. Detect and remove all data outliers determined in steps 3 and 4.

6. Analyze the local geoid in detail.

    a. Plot the modeled geoid heights in the area.
    b. Plot the estimated slope of the geoid using differences between GPS-derived ellipsoid height differences and leveling-derived orthometric height differences (dN = dh - dH) obtained in step 4.

7. Estimate GPS-derived orthometric heights and local systematic errors in the geoid heights by solving for the geoidal slope and scale using the method described in Vincenty (1987) and demonstrated in Zilkoski and Hothem (1989) and Zilkoski (1990a).

8. Compare adjusted GPS-derived orthometric height differences from step 7 with leveling-derived orthometric height differences to determine scale and rotation parameters.

9. Compare GPS-derived orthometric heights by performing a 3-dimensional least squares adjustment holding fixed all appropriate orthometric height values of published bench marks (and approximate GPS-derived coordinates computed from higher-order surveys and solving for appropriate scale and rotation parameters.

10. Use the results from steps 1 through 9 to document the estimated accuracy of the GPS-derived orthometric heights.

APPENDIX D. – Brief Description of Guidelines Using Sample Project.

Using GPS, Geoid99, and NGS Guidelines to Obtain Reliable, Accurate Orthometric Heights in Support of Photogrammetric and Surveying Project in Baltimore County, Maryland

Three Basic Rules

The project fulfilled the three basic rules by :

Following NGS’ guidelines for establishing GPS-derived ellipsoid heights (Standards: 2 cm and 5 cm);

using GEOID99, the latest National Geoid Model; and

using NAVD 88, the latest National Vertical Datum.

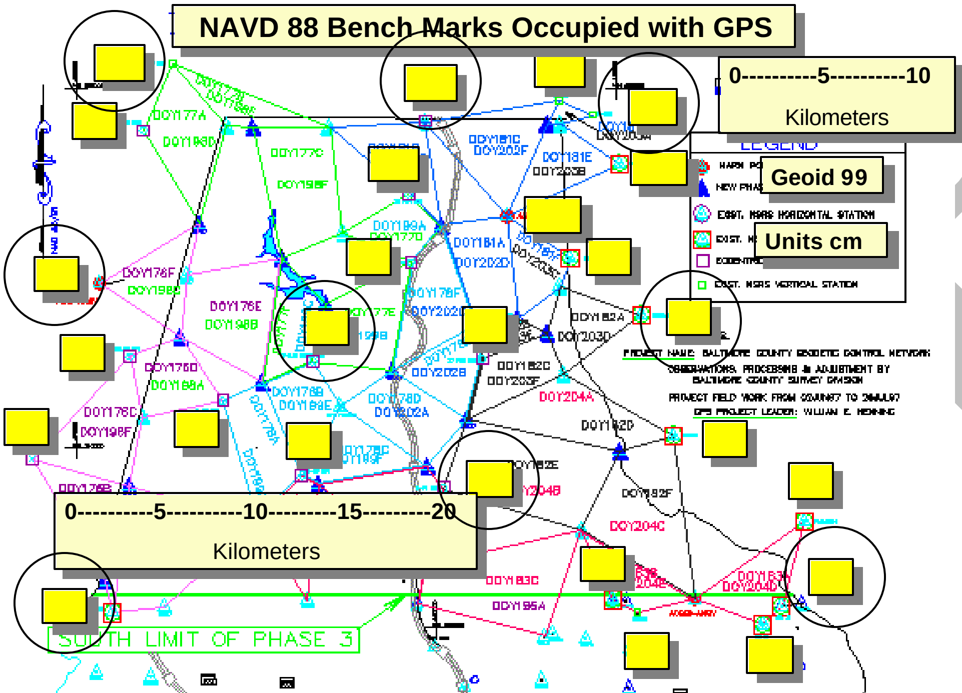
Four Basic Control Requirements

BCR1:Occupy stations with known NAVD 88 orthometric heights (Stations should be evenly distributed throughout project)

BCR2:Project areas less than 20 km on a side, surround project with NAVD 88 bench marks, i.e., minimum number of stations is four; one in each corner of project

BRC3:Project areas greater than 20 km on a side, keep distances between GPS-occupied NAVD 88 bench marks to less than 20 km

BRC4:Projects located in mountainous regions, occupy bench marks at base and summit of mountains, even if distance is less than 20 km



BCR1: Stations with large blocks have NAVD 88 heights and they are evenly distributed throughout the project area.

BCR2: This requirement is not applicable because the project is greater than 20 km on a side. [If the project was less than 20 km on a side, then there should be at least four stations with NAVD 88 heights, i.e., four large blocks , one in each corner of the project.]

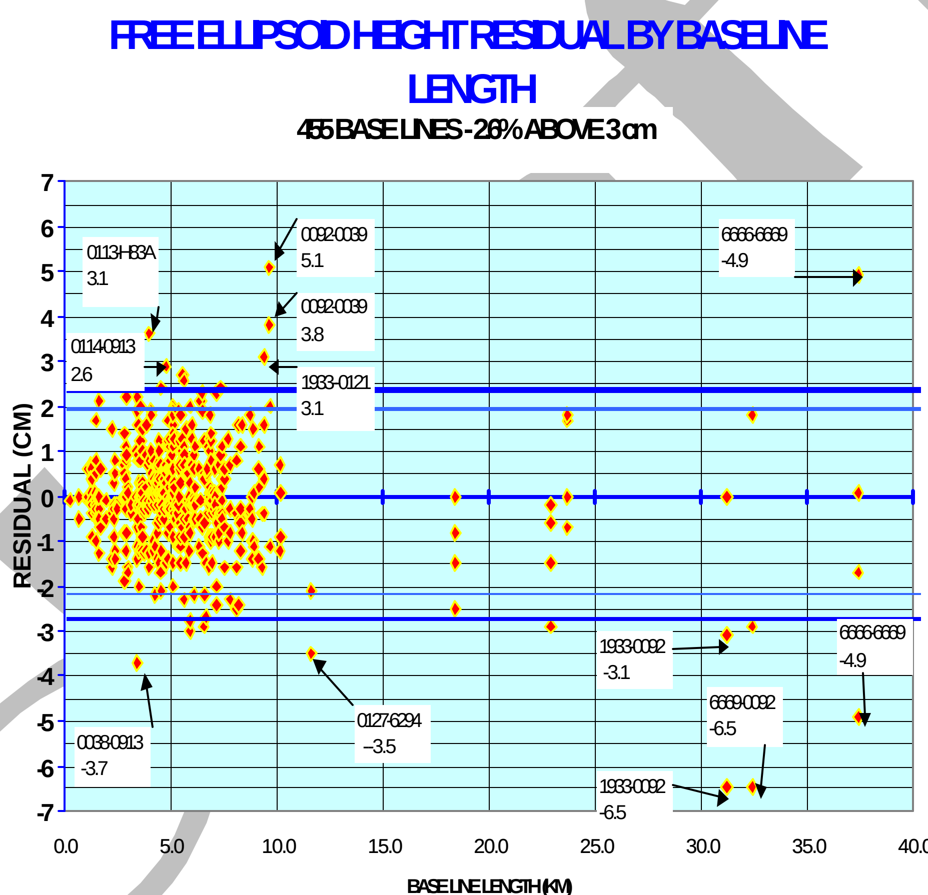
BCR3: Circled bench marks are mandatory. The analysis must determine that the bench marks have valid NAVD 88 heights. Other bench marks can be substituted but the user must adhere to the 20 km requirement.

[NOTE: Valid NAVD 88 height values include, but are not limited to, the following: bench marks which have not moved since their heights were last determined, were not misidentified, and are consistent with NAVD 88.]

BRC4: This requirement is not applicable because project is not in a mountainous region. [If the project was in a mountainous region then bench marks should be located at the base and summit of the mountainous region.]

BAP1:Perform a 3-D minimum-constraint least squares adjustment of the GPS survey project, i.e., constrain one latitude, one longitude, and one orthometric height value.

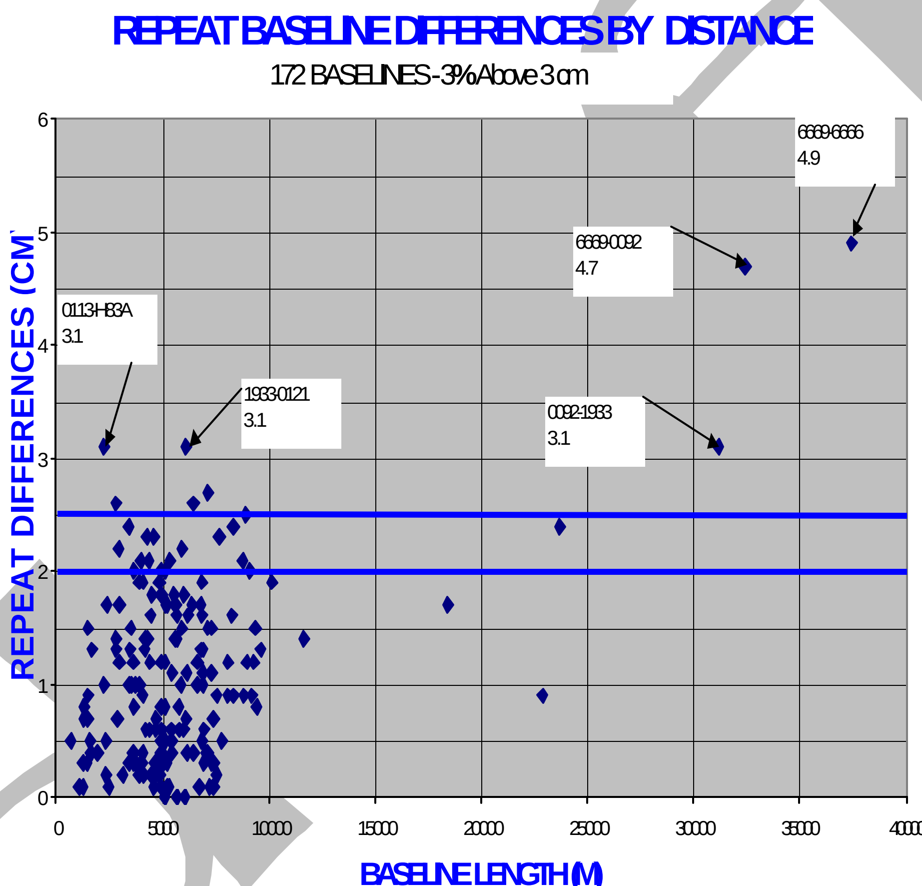
BAP2:Using the results from the adjustment in procedure 1 above, detect and remove all data outliers. The user should repeat procedures 1 and 2 until all data outliers are removed.



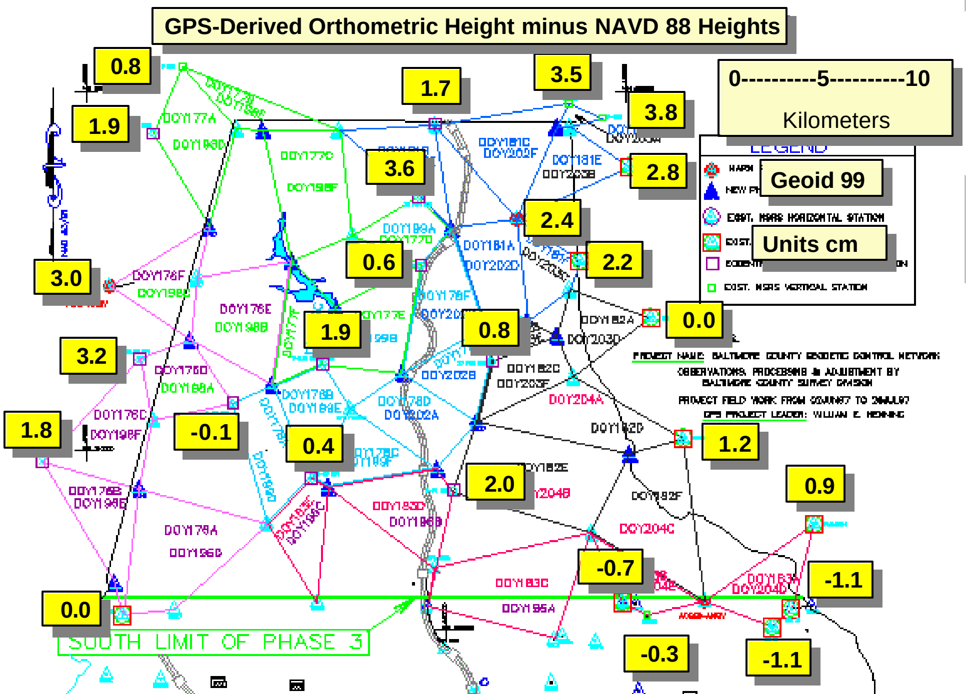
Note: After performing the minimum constraint adjustment, the user should plot the ellipsoid height residuals (or dU residuals) and investigate all residuals greater than 2 cm.

Note that the station pairs that have large residuals, i.e., greater than 2.5

cm, also have large repeat base line differences. The NGS guidelines for estimating GPS-derived ellipsoid heights require the user to reobserve these base lines. Following NGS guidelines provides enough redundancy for the adjustment process to detect outliers and apply the residual on the appropriate observation, i.e., the bad vector.

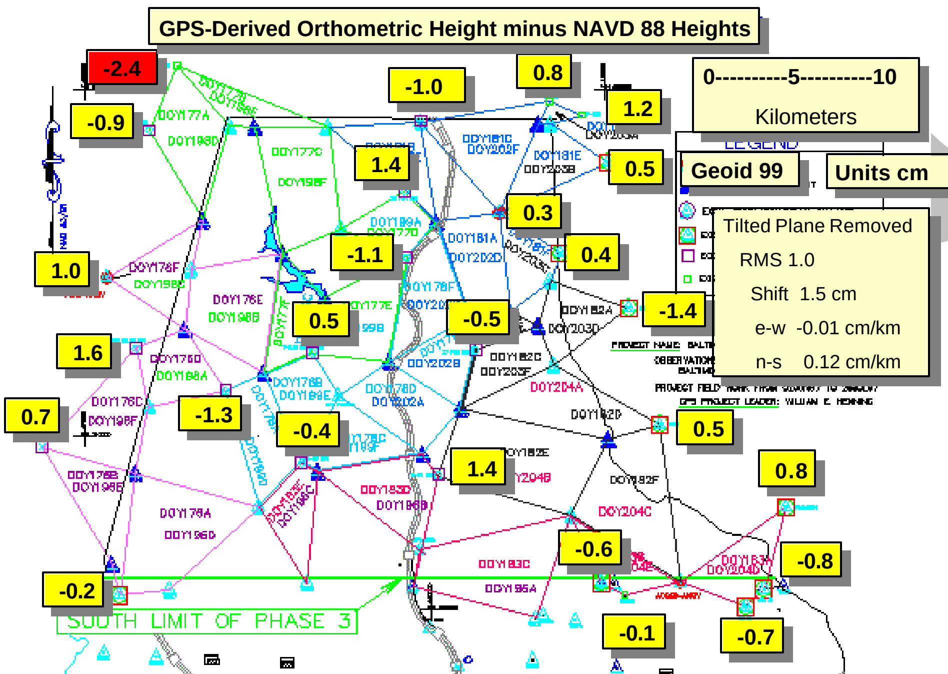


BAP 3: Compute differences between the set of GPS-derived orthometric heights from the minimum constraint adjustment from procedure 2 above and published NAVD 88 bench marks.



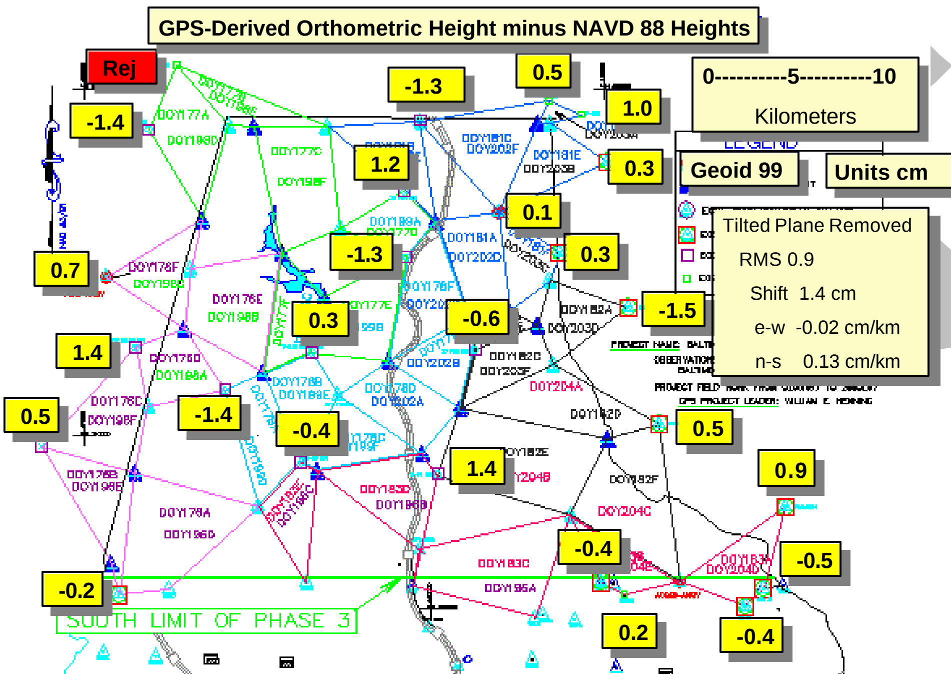
Note: All height differences are under 5 cm and most are less than 2 cm. Almost all relative height differences between adjacent station pairs are less than 2 cm. However, most of the height differences appear to be positive relative to the southwest corner of the project

BAP 4: Using the results from procedure 3 above, determine which bench marks have ***valid*** NAVD 88 height values. All differences between valid bench marks need to agree within 2 cm for 2-cm surveys and 5 cm for 5-cm surveys



Note: To detect and remove any systematic trend, a tilted plane is best fit to the height differences (Vincenty 1987, Zilkoski and Hothem 1989). After a trend has been removed, all the differences are less than +/- 2 cm except for one and almost all relative differences between adjacent station are less than 2 cm.

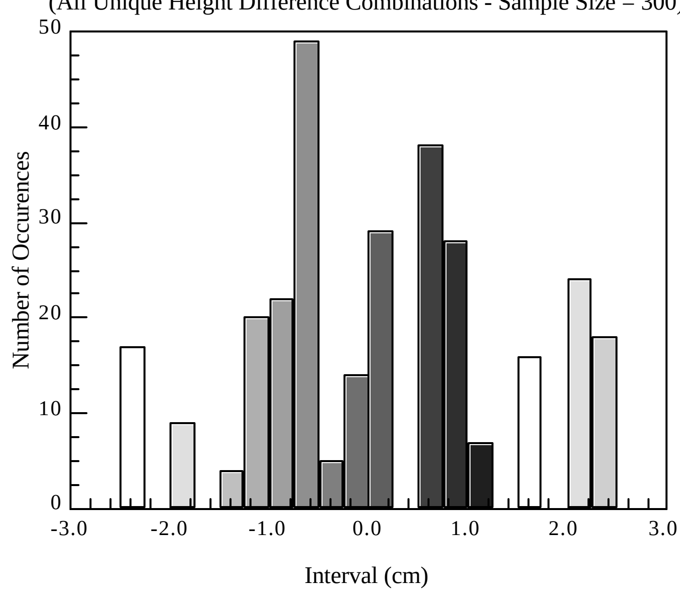
BAP 5: Using the results from procedure 4 above, perform a constrained adjustment fixing one latitude and one longitude value and all ***valid*** NAVD 88 height values.

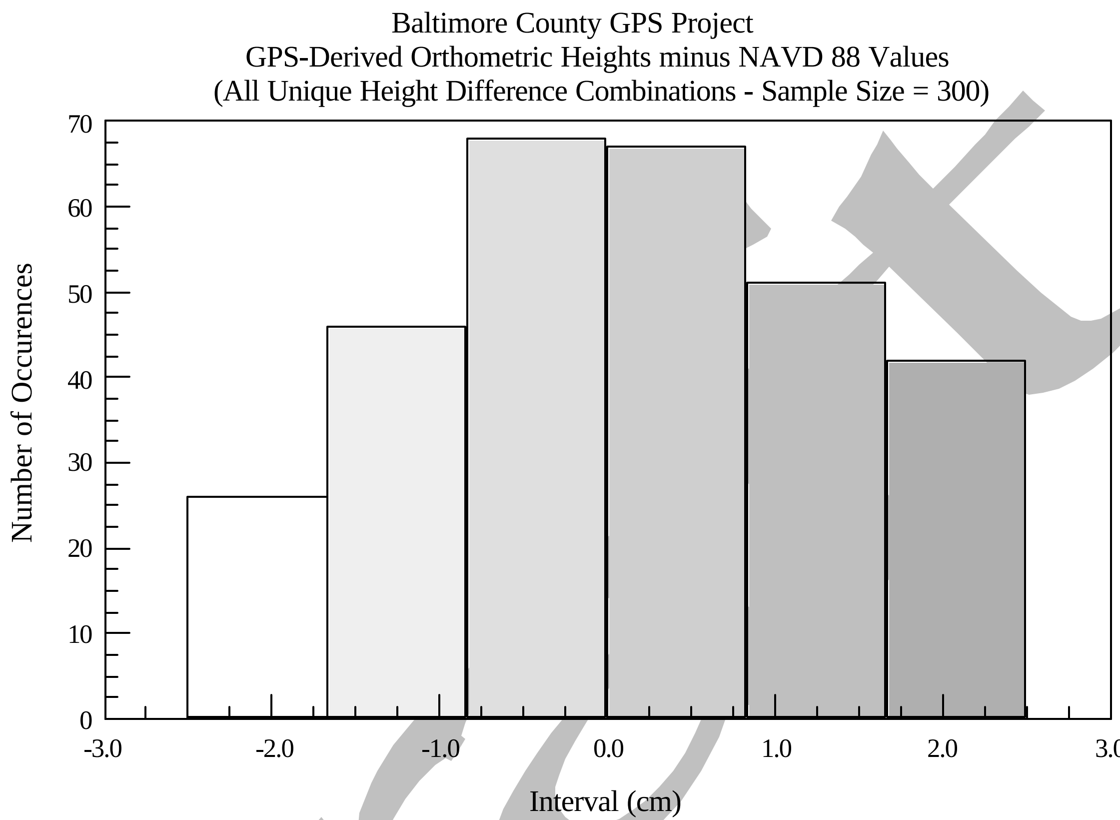


Note: After rejecting the largest height difference (-2.4 cm), of all the closely spaced station pairs, i.e., less than 10 km, only three are greater than 2 cm, one is greater than 2.5 cm and none are greater than 3 cm.

There are 25 stations with both GPS heights and NAVD88 heights. This makes 300 unique comparisons. Of these comparisons, 59 are greater than 2.0 cm but only 34 are greater than 2.1 cm, and none are greater than 2.5 cm.

Baltimore County GPS Project
GPS-Derived Orthometric Heights minus NAVD 88 Values
(All Unique Height Difference Combinations - Sample Size = 300)




Baltimore County GPS Project
GPS-Derived Orthometric Heights minus NAVD 88 Values
(All Unique Height Difference Combinations - Sample Size = 300)
Number of Occurences
0
10
20
30
40
50
60
70
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
Interval (cm)